Star formation history in the solar neighborhood: the link between stars and cosmology *

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Abstract. Using a cosmological galactic evolutionary approach to model the Milky Way, we calculate the star formation history (SFH) of the solar neighborhood. The good agreement we obtain with the observational inferences suggests that our physical model describes accurately the long term/large spatial trends of the local and global Milky Way SFH. In this model, star formation is triggered by disk gravitational instabilities and self-regulated by an energy balance in the ISM. The drivers of the SFH are the cosmological gas infall rate and the gas surface density determined by the primordial spin parameter. A ΛCDM cosmology was used throughout.

Keywords: cosmology: dark matter — Galaxy: evolution — Galaxy: halo — galaxies: formation — solar neighborhood — stars: formation

1. Introduction

Galaxies are the "ecosystems" where stars are born and evolve interacting with the ISM. On the other hand galaxies are the structural units of the universe as a whole. Thus, the study of galaxy formation and evolution connects in a natural way stellar and ISM astrophysics with cosmology. The Milky Way (MW) is among the best studied galaxies, in particular at the solar neighborhood. The available observations for the solar neighborhood provide valuable information not only about its present-day properties but also about its past history. For example, the possibility of resolving stars and constructing a color-magnitude diagram (CMD) for the solar neighborhood allows us in principle to recover its star formation history (SFH).

Star formation (SF) is a key ingredient for galaxy formation and evolution. Most models of galaxy formation in a cosmological context extend the hierarchical assembly of cold dark matter (CDM) halos to luminous galaxies using *ad hoc* and/or empirical recipes for calculating the SF (e.g., White & Frenk 1991; Kauffmann, White, & Guiderdoni 1993; Baugh, Cole, & Frenk 1996). An important improvement in this kind of approaches is to link the SF process to the structure, dynamics and hydrodynamics of modeled galaxies, and to test the model with detailed observations, for example the SFH in the solar neighborhood.

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We have developed an approach of disk galaxy formation and evolution in a cosmological context which includes a physically self-consistent scheme to calculate the SF process of the growing disk (Firmani & Avila-Reese 2000; Avila-Reese & Firmani 2000, hereafter FA00 and AF00 respectively). Using this approach and in the light of the available observational information, we will explore the drivers of the local and global SFH in the MW and their potential connection to the cosmological background.

2. Observational inferences

An objective inference of the SFH in the solar neighborhood comes from by comparing synthetic CMDs to the observed one (e.g., Chiosi et al. 1989). These CMD inversion methods have been improved more recently with a more rigorous statistical analysis (Tolstoy & Saha 1996; Hernández, Valls-Gabaud & Gilmore 2000 and more references therein). For example, the advanced Bayesian analysis introduced by Hernández et al., allows the recovery of the underlying SFH without the need of assuming any *a priori* SFH. With the *Hipparcos* catalog the time resolution of this technique is ~ 0.05 Gyr, however, the age range which it allows to explore is small (the last 3 Gyr); this limitation is related to the incompleteness of the catalog. With a standard parametric maximization technique, Bertelli & Nasi (2001) were able to recover the SFH along the whole life of the disk solar neighborhood, at expenses of a low time resolution. Their method is useful to describe only the *general trend of the SFH over the total life of the system*, and not its detailed shape. The robust conclusion we can extract from this study is that the average SF rate (SFR) over the period 10-6 Gyr (in look back time) could not have been larger than that over the 6-0 Gyr period. In Fig. 1a, we plot the surface SFR $\dot{\Sigma}_{\rm s}$ vs. look back time corresponding to the solution for the model with more degrees of freedom of those used in Bertelli & Nasi (jointed circles). That the solar neighborhood SFR in the past could not have been very different from the present-day one is also suggested by the birthrate parameter b and the differential metallicity distribution of G-dwarfs (e.g., Boissier & Prantzos 1999).

A quantity more accurately determined than the SFH shape, is the look back time at which stars began to form in the solar neighborhood. Using the photometric and kinematic data of the *Hipparcos* satellite, Binney, Dehnen, & Bertelli (2000) inferred an age for the disk at the solar radius of 11.2 ± 0.75 Gyr (horizontal shaded box in Fig. 1a). Regarding its present-day SFR, observational inferences give values around $3-5$ $\rm M_{\odot}Gyr^{-1}pc^{-2}$ (vertical shaded box).

Methods alternative to the CMD inversion have been also used to infer the SFH in the solar neighborhood, among them the construction of the stellar age distribution using the empirical correlation of chromospheric activity in G-K dwarfs with their age (e.g., Rocha-Pinto et al. 2000; see references on other methods therein). These methods are subject of strong observational uncertainties and biases. For example, the chromospheric activity-age relation presents a strong scatter of around a factor 2 in age which should be included as a time smoothing kernel on the inferred SFH. Interestingly, if such a smoothing is applied on the results of Rocha-Pinto et al. (2000), a trend similar to that reported in Bertelli & Nasi (2001) appears.

3. A theoretical approach

As it was discussed above, the observational data in the solar neighborhood allow to infer a general trend of its SFH, which due to stellar diffusion it may actually correspond to the average SFH of an annulus of $\sim 2-3$ kpc. We will present predictions regarding local and global SFHs for the MW modeled using a deductive disk galaxy evolution approach (FA00; AF00). This approach is based on the hierarchical formation scenario, assuming that disks form by gas accretion more than by repeated merging of sub-unities which would destroy the disk. A brief description of our approach is as follows:

A disk forms *inside-out* within a growing CDM halo. The evolution of the halo is set by its mass aggregation history (MAH). For a given present-day total virial mass M_v, a statistical set of MAHs is calculated from the initial Gaussian density fluctuation field once the cosmology and power spectrum are fixed (Avila-Reese, Firmani & Hernández 1998). Given the MAH, the halo density profile is calculated with a generalization of the secondary infall model, based on spherical symmetry and adiabatic invariance, but allowing for non-radial orbits (Avila-Reese et al. 1998). The halo density profile depends on the MAH. The average MAH yields density profiles very close to the Navarro, Frenk & White (1997) profile, while the other less probable MAHs yield a variety of density profiles which also agree with what is found in N-body cosmological simulations (Avila-Reese et al. 1998, 1999). A fraction f_d of the mass of each collapsing spherical shell is transferred in a virialization time into a central disk gas layer. Assuming angular momentum conservation, a given gas element of the shell falls into the equatorial plane at the position where it reaches centrifugal equilibrium. The specific angular momentum of each shell is obtained from the derivative of λ, assumed to be constant in time. We calculate the

halo contraction due to the gravitational drag of the infalling gas. A nearly exponential disk surface density arises naturally in this inside-out scheme of disk formation. The λ parameter determines the scale length and surface density of the disk.

Star formation. SF at a given radius in the gaseous disk is triggered by gravitational instabilities, i.e. whenever the Toomre parameter $Q_g(r)$ is less than a given threshold, q (numerical and observational studies suggest $q \approx 2$). The SF rate (SFR) is calculated from the equation that relates the energy input rate (mainly due to SNae) to the (turbulent) energy dissipation rate assuming that $Q_g(r)$ is always equal to q at all radii, i.e. we allow only for the stationary solution of a *self-regulated* SF mechanism (Firmani & Tutukov 1994; Firmani, Hernandez, & Gallagher 1996). A key parameter in this scheme is the turbulent dissipation time $t_d(r)$ which we approximate as in Firmani et al. (1996). Estimates of $t_d(r)$ for the solar neighbourhood obtained in compressible magneto-hydrodynamic simulations of the ISM (Avila-Reese & Vázquez-Semadeni 2001) are in agreement with the Firmani et al. approximation. The evolution of the stellar populations is followed with a parametrization of simple population synthesis models. A Salpeter IMF with minimal and maximal masses of $0.1\mathrm{M}_\odot$ and $100\mathrm{M}_\odot$, and solar metallicities were used. The azimuthally averaged dynamics of the evolving gas and stellar disks coupled with the dark halo are treated by solving the corresponding hydrodynamical equations.

Modeling the Milky Way. For a given cosmology (here: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 65$ km s^{-1}Mpc^{-1}, $\sigma_8 = 0.9$) a galaxy model is completely determined by the virial mass $\mathrm{M_v}$, the MAH, the spin parameter λ, and the disk mass fraction $\mathrm{f_d}$. These factors and their statistical distribution are related to the cosmological background, and we have shown that they are able to produce disk galaxies which match the Tully-Fisher relation and its scater, and several correlation across the Hubble sequence (FA00; AF00). In order to calculate a model representative of the MW, we have to chose correctly these input factors. Fortunately, each one of them is tightly related to a present-day MW feature, although with some (small) degeneracy. In Hernandez, Avila-Reese & Firmani (2001, HAF01) we showed that the sensitivity of the local SFH to this degeneracy and to the uncertainty of the observables that constrict the input parameters are small.

The MAH determines mainly the galaxy color index. Unfortunately the MAH cannot be described by one simple parameter and the color index of the MW is not well determined. Therefore, does not make sense to fix a very particular MAH for the MW. We shall use the most probable realization of the MAHs (the average one), but we also

Table I. Properties of the MW: observations and model results

Observable	Predicted value [a]	Observed value
$V_c(50)$ [b] [km s^{-1}]	208	206 ± 10
r_s [kpc]	3.0	3.0 ± 0.5
M_s [c] [10^{10} $M_\odot$]	4.4	4-5
M_v [10^{12} $M_\odot$]	2.8	1-4
V_{max} [d] [km s^{-1}]	235	220 ± 10
L_B [$10^{10} L_{B_\odot}$]	1.7	1.8 ± 0.3
r_B [e] [kpc]	4.3	4-5
$\Sigma_{0,K}$ [f] [$L_{K\odot} pc^{-2}$]	810	1000 ± 200
f_g	0.23	$0.15 - 0.20$
SFR [$M_\odot yr^{-1}$]	2.9	2-6
Solar neighborhood		
Σ_s [$M_\odot pc^{-2}$]	41.3	43 ± 5 [g]
Σ_g [$M_\odot pc^{-2}$]	13.6	13 ± 3
$\dot{\Sigma}_s$ [$M_\odot Gyr^{-1}$ pc^{-2}]	3.1	3-5
$B - K$ [mag]	3.15	3.13

[(a)] The MW model was obtained tuning three input parameters in order to reproduce the first three quantities, which are constraints and not predictions. [(b)] Circular (asymptotic) velocity at 50 kpc. [(c)] Stellar (disc+bulge) mass. [(d)] This maximum rotation velocity does not take into account the nuclear and bulge region and it is for Galactocentric radii smaller than 15 kpc. [(e)] $B-$band disc scale length. [(f)] Disc central surface brightness in the $K-$band, taking a mass to light ratio of 1.0 for this band. [(g)] This estimate includes the contribution of stellar remnants.

will explore other possible MAHs. As a matter of fact, the $B - K$ color estimated for the MW disk (~ 3.3, see Kent et al. 1991 for the $K-$magnitude estimate) is similar to the average color of galaxies of its type, suggesting that the MW is indeed an average galaxy.

The total mass M_v, the spin parameter λ, and the disk mass fraction M_d are fixed in such a way that the modeled MW obeys the observable constraints related to these parameters: the circular velocity at 50 kpc, the disk scale lenght r_s, and the disk+bulge mass, mainly the mass contained in stars, M_s. For the average MAH, these constraints fix $M_v = 2.8\ 10^{12} M_\odot$, $\lambda = 0.02$, and f_d=0.021 (the fiducial model). For this model the constraints and predictions, and the corresponding observational estimates are given in Table 1 (see HAF01 for the references). The shortcoming of the model is an excesively peaked rotation curve w.r.t.

observations. This is associated with the large central concentrations of CDM halos. The predicted SFH does not change significantly if a shallow core is introduced in the MW CDM halo (HAF01).

Predicted local and global star formation histories. In Fig. 1a we show the SF and gas infall histories, $\dot{\Sigma}_s$ and $\dot{\Sigma}_g$, of the fiducial model at the radius $R_0 = 8.5$ kpc. There is a remarkable agreement with the observational estimates. The disk at R_0 begins to form at look back time ~ 11 Gyr ($z \approx 2$), the SFR attains a maximum at $8 - 6$ Gyr ($z \approx .9 - .6$) and then it decreases by a factor of ~ 2 towards the present. With these SF and gas infall histories the present-day stellar and gas surface densities are 41.3 and 13.8 $M_\odot pc^{-2}$, respectively.

In HAF01 we have experimented with a wide range of MAHs (the MAH influences stonghly the SFH), and we have found that the SFH predicted with the most probable (average) MAH is the best in matching the observational data. Using Padova stellar evolutionary models we computed synthetic CMDs for this SFH taking a solar metallicity for the last 2 Gyr, and one third the solar before, as a first approximation to the enrichment history. The obtained $B-K$ color index is 3.15, in excellent agreement with estimates for the solar neighborhood, $B-K = 3.13$ (Binney & Merrifield 1999). In the future we shall compare directly the *Hipparcos* CMD with our theoretical CMD (thanks to A. Bressan for suggesting this to us). Repeating the experiment for SFHs resulting from other MAHs, we obtain $B - K$ colors up to 0.25 mag redder and 0.15 mag bluer than 3.15. Again, the average MAH seems to be the optimal choice for the Galaxy.

The global SF and gas infall histories (in $M_\odot$ yr^{-1}) for the fiducial MW model are shown in Fig. 1b. The maximum SFR is attained at $z \approx 1.3$, then decreases by a factor of 1.5 towards $z = 0$. A nearly constant SFH is a common feature in the evolution of our modeled disk galaxy population. Our predicted SF and gas infall histories do not deviate from the constraints of the phenomenological chemo-spectrophotometric models (e.g., Boissier & Prantzos 1999). Therefore, we can expect our model to be also in agreement with the data regarding metallicities and abundance gradients in the solar neighborhood and the Galaxy.

4. Drivers of the SFH and concluding remarks

Within our SF scheme, the two important drivers of the SFH are the gas infall history and the gas disk surface density. The former is related to the cosmological MAH while the latter depends mainly on the spin parameter λ. For a roughly $1 - \sigma$ range in the MAHs and λ's, most of

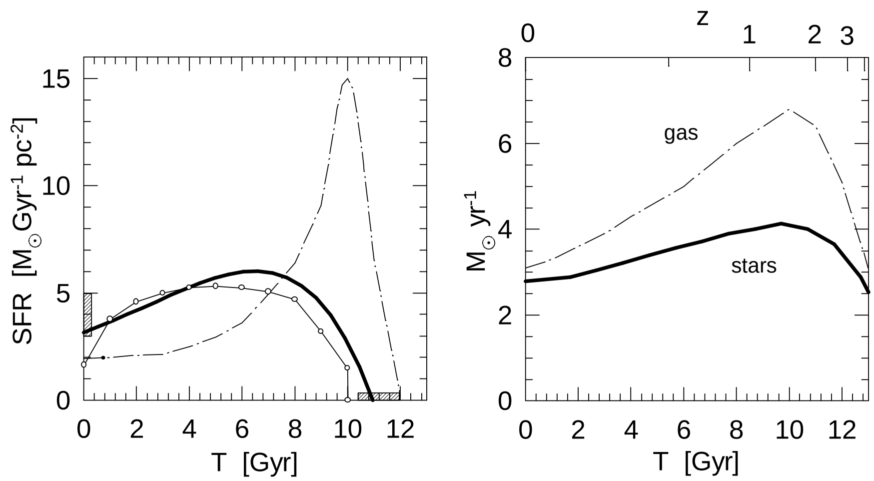

Figure 1. *(a) Left:* Surface SF and gas accretion histories for the solar neighbourhood corresponding to the fiducial model (thick solid and dot-dashed lines). The jointed circles give the inferences of Bertelli & Nasi 2001, and the boxes are independent observational estimates for the age of the solar neighborhood and its present-day SFR. *(b) Rigth:* Global SF and gas accretion histories for the fiducial MW model.

the predicted global SFHs of disk galaxies present a shallow maximum at $z \approx 1-2.5$ and then slightly decrease until $z = 0$ by a factor < 3 (see Fig. 1b, for the case of a MW-like galaxy). The shape of the SFH of the universe inferred from high-redshift observations does not agree with this nearly constant behaviour of the SFH of disk galaxies, suggesting that other galaxy populations (starburst dwarfs?, bulges?, ellipticals?) dominated at larger redshifts in the integral SFR of the universe.

The local SFH (e.g. at radius R_0) also is controled by the (cosmological) gas infall history and the local gas surface density. The stationary self-regulation mechanism combined with the disk gravitational instability triggering criterion lead to a $\dot{\Sigma}_{\rm s}(r) \propto {\Sigma_{\rm g}}^n$ law, with $n \approx 2$ in rough agreement with observations. In the light of our inside-out scenario, the formation epoch T of the MW disk at a given radius (e.g. R_0) depends on the angular momentum of the infalling gas, i.e. on λ. On the other hand, λ determines $\rm r_s$. Interestingly, once we fixed λ to reproduce the observed $\rm r_s$, the predicted T_0 is in agreement with the observational estimates, suggesting that T_0 and $\rm r_s$ could indeed be related to the only parameter λ. Note that we have used $H_0 = 65$ km s^{-1}Mpc^{-1}; cosmic time is inversely proportional to H_0, so that the predicted T_0 also depends on H_0. A similar connection, although more trivial, appears to

be related to the $B-K$ color index of the solar neighborhood and its SFH. According to our model, both of them are related to the MAH, and for the average MAH the predictions agree with the observational inferences.

The overall self-consistency of our cosmological MW model predictions and the agreement found with the inferred SFHs in the solar neighborhood, suggest that the main ingredients of the SF process in the MW were correctly taken into account. Our stationary solution may represent the long term/large spatial trends of the SFH in the solar neighborhood. Complementary mechanisms of SF or SF enhancement could introduce fluctuations of short temporal and spatial character.

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